Chemical Science Review and Letters ISSN 2278-6783
www.chesci.com Research Article

Effect of Sulphur Nutrition and Bio-fertilizer Inoculation on Growth and Yield of Fenugreek (*Trigonella foenum-graecum* L.)

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Abstract

A field experiment was conducted during the *rabi* season of 2025–26 at the Research Farm of Vivekananda Global University, Jaipur (Rajasthan) to evaluate the impact of varying sulphur levels (10, 20, 30, and 40 kg S ha^{-1}) and bio-fertilizer inoculations (Control, *Rhizobium*, *Rhizobium* + PSB, and NPK Consortia) on the growth, yield, and nutrient dynamics of fenugreek (Variety: PRM-45). The experiment was arranged in a Factorial Randomized Block Design (RBD) with three replications. The results revealed that the application of 40 kg S h^{-1} significantly enhanced growth parameters (plant height, dry matter accumulation, and effective root nodulation), yield attributes (pods per plant, pod length, and seeds per pod), and productivity, yielding the highest seed yield 1896 kg ha^{-1} and haulm Yield 4860 kg ha^{-1}). Among the bio-fertilizers, seed inoculation with NPK Consortia (a mixture of *Rhizobium* + PSB + KSB) achieved top tier performance, remaining statistically at par with the dual inoculation of *Rhizobium* + PSB. NPK Consortia substantially boosted seed yield 1796kg ha^{-1} and haulm yield 4663kg ha^{-1} over single inoculation and control setups.

Keywords: Biofertilizers, NPK consortia, Sulphur,KSB

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Introduction

Fenugreek (*Trigonella foenum-graecum* L.), widely recognized by its vernacular name "methi," is an indispensable winter season legume spice crop predominantly cultivated in the arid and semi-arid tracts of India. Renowned for over 2,500 years for its restorative and nutraceutical properties, its seeds contain the alkaloid trigonelline 0.12 % -0.38%, which assists in reducing glycosuria in diabetic patients. Fenugreek exhibits exceptional therapeutic value, including anti-diabetic, hypocholesterolaemic, anti-microbial, and anticancer effects. It serves as an essential source of diosgenin 0.86-2.2%, a steroid saponin utilized as an estrogen precursor and in sex hormone synthesis.

At the national level, India dedicates 117,294 hectares to fenugreek cultivation, generating an annual production of 185,170 tonnes and average productivity: 1600 kg ha^{-1}. Rajasthan leads this production, spanning 55,000 hectares with an output of 70,000 tonnes and average productivity 1273kg ha^{-1}, focused heavily within districts like Sikar, Chittorgarh, Jaipur, Pali, and Nagaur. Sulphur is recognized as the fourth critical macronutrient following nitrogen, phosphorus, and potassium. Intensive cropping with high-analysis, sulphur-free fertilizers (e.g., Urea and DAP) has induced a structural sulphur deficiency—or "hidden hunger"—across Rajasthan's light-textured soils. As an structural component of essential amino acids (methionine, cysteine, and cystine), sulphur plays a fundamental role in chlorophyll synthesis, enzyme activation, and effective root nodulation for atmospheric nitrogen fixation.

Simultaneously, relying exclusively on chemical inputs diminishes nutrient use efficiency, degrades soil physical-biological dynamics, and strains farmers financially. Integrated Nutrient Management (INM) via bio-fertilizers presents a viable pathway forward. Introducing effective microbial strains through an NPK Consortia (*Rhizobium* + Phosphate Solubilizing Bacteria + Potassium Solubilizing Bacteria) enhances the biological fixation of N, solubilizes bound P, and mobilizes mineral K.

Materials and Methods

The field trial was executed during the *rabi* season of 2025–26 at the Research Farm of Vivekananda Global University, Jaipur, Rajasthan. The experiment carried out through sulphur levels (10, 20, 30, and 40 kg S ha^{-1}) and bio-fertilizer inoculations (Control, *Rhizobium*, *Rhizobium* + PSB, and NPK Consortia) in Factorial Randomized Block Design

(RBD) featuring sixteen treatment combinations replicated three times across forty-eight distinct plots. As per recommendation, 40 kg N+ 20 kg P_2O_5 ha^{-1} was applied. Urea and DAP were used as a source of nitrogen and phosphorus, respectively. The whole quantity of sulphur was applied as per treatment allocation at the time of sowing along with recommended dose of nitrogen and phosphorus. Bentonite (90 % sulphur) was used as a source of sulphur. The seeds were treated with liquid bio-fertilizers *Rhizobium*, *Rhizobium* + PSB and NPK Consortia using 5ml kg^{-1} through standard procedure 2-3 hours before sowing as per treatment allocation. Fenugreek seeds were inoculated with Rhizobium, Phosphate Solubilizing Bacteria (PSB) and NPK Consortia as per treatment details. The Rhizobium culture contained *Rhizobium leguminosarum* strain with a minimum viable cell count of 1×10^8 CFU mL^{-1}. The PSB inoculant contained phosphate-solubilizing bacterial culture with a minimum population of 1×10^8 CFU mL^{-1}. The NPK Consortia contained compatible strains of Rhizobium, PSB and Potassium Solubilizing Bacteria (KSB) with a minimum viable count of 1×10^8 CFU mL^{-1}. The cultures were procured from a certified bio-fertilizer production unit and were used within the recommended shelf life of six months. The inoculants conformed to FCO quality specifications regarding viable cell count and contamination level. The Pratap Rajasthan Methi (PRM-45) is a high yielding variety of fenugreek having yield potential of 18-20 q ha^{-1} released by MPUAT, Udaipur in 2015 which matures between 120-125 DAS. The growth efficiency parameters mainly CGR and RGR were estimated between 30-60 DAS, 60-90 DAS and 90 DAS to harvest by the following formula as given by Radford (1967).

$$Crop\ growth\ rate\ (g\ m-^2\ day-^1) = \frac{1}{P} x \frac{W_2 - W_1}{t_2 - t_1}$$

$$RGR = \frac{log_e W_2 - log_e W_1}{T_2 - T_1}$$

The data recorded for evaluation of treatments were subjected to statistically analysis by applying techniques of analysis of variance as advocated by Fisher and Yates (1949).

Result and Discussion

Effect of sulphur

Growth Characters

The results revealed that application of sulphur up to 40 kg ha^{-1} significantly improved growth parameters of fenugreek, including plant height, branching and dry matter accumulation. The maximum biomass production at harvest (23.36 g $plant^{-1}$) was recorded under 40 kg S ha^{-1}, which was significantly higher over lower sulphur levels.

The improvement in growth may be attributed to the essential physiological role of sulphur in plant metabolism. Sulphur is a key constituent of sulphur-containing amino acids such as methionine and cystine, which are essential for protein synthesis and enzymatic activity. It also enhances chlorophyll formation and photosynthetic efficiency, thereby improving overall plant vigor. Further, sulphur application improves nutrient availability through mild acidification of calcareous soils, enhancing the availability of phosphorus and micronutrients such as Fe, Zn and Mn. This improved nutrient uptake stimulates meristematic activity, resulting in better cell division, elongation and differentiation, which ultimately increases plant height and branching.

Enhanced nodulation under sulphur application further improved biological nitrogen fixation, which contributed to better nitrogen availability and higher photosynthetic activity. Consequently, increased dry matter accumulation was observed. The strong positive correlation between dry matter accumulation and plant height and branching confirms the interdependence of these growth parameters. These results are in agreement with findings of Godara et al. (2013), Choudhary et al. (2014) and Verma et al. (2019), who also reported improved growth of fenugreek with sulphur application.

Yield Attributes and Yield

Application of sulphur up to 40 kg ha^{-1} significantly improved yield attributes such as pods per plant, seeds per pod, pod length and test weight. Consequently, seed, haulm and biological yield increased significantly, while harvest index remained unaffected.

The improvement in yield can be attributed to better vegetative growth and enhanced source–sink relationship under sulphur nutrition. Increased dry matter production and higher crop growth rate ensured greater assimilate availability during reproductive stages, leading to improved pod formation, seed setting and seed filling.

The positive correlation between yield attributes and seed yield confirms their direct contribution to productivity. Improved test weight was associated with higher nitrogen and sulphur concentration in seeds, indicating better nutrient translocation to developing grains. Haulm yield increased due to enhanced plant height and branching, while biological yield increased as a combined effect of higher seed and straw production. These findings are supported by Yadav (2011), Lal et al. (2015) and Manohar et al. (2017), who also reported similar responses in fenugreek.

Table 1. Various treatments and effects.

Treatments	Plant population	Plant height (cm)				Dry matter accumulation (g plant-1)				CGR (g m-2 day-1)			RGR (g g-1 day-1)		
		30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest	30 - 60 DAS	60 – 90 DAS	90 DAS – at harvest	30 - 60 DAS	60 – 90 DAS	90 DAS –at harvest
Sulphur (kg ha-1)															
10	9.59	5.48	46.44	70.04	75	0.332	4.07	11.7	17.55	4.05	8.38	6.39	0.0793	0.036	0.0134
20	9.74	5.62	50.52	73.55	80.36	0.358	4.37	13.01	19.61	4.35	9.50	7.24	0.0793	0.0361	0.0136
30	9.86	5.69	53.08	76.53	84.19	0.384	4.71	14.05	21.61	4.70	10.58	7.28	0.0798	0.036	0.0143
40	9.95	5.73	56.08	79.65	88.02	0.399	5.03	15.25	23.36	5.05	11.25	8.91	0.081	0.0367	0.0143
S.Em.±	0.06	0.03	0.77	0.9	1.17	0.02	0.01	0.2	0.18	0.06	0.19	0.06	0.0006	0.0009	0.0007
C.D.	NS	NS	2.42	2.79	3.57	0.01	0.16	0.66	0.61	0.14	0.74	0.36	NS	NS	NS
Bio-fertilizers															
Control	9.50	5.09	46.52	70.98	77.07	0.347	4.19	11.68	17.65	4.13	8.34	6.03	0.0787	0.0353	0.0134
Rhizobium	9.82	5.5	51.06	74.18	80.77	0.365	4.5	13.29	20.13	4.49	9.75	7.50	0.0798	0.0358	0.0138
Rhizobium + PSB	9.88	5.95	54.13	77.15	84.72	0.377	4.73	14.38	21.9	4.74	10.70	8.25	0.0804	0.0369	0.0139
NPK consortia	9.93	5.99	54.4	77.47	84.99	0.38	4.79	14.65	22.45	4.80	10.93	8.04	0.0805	0.0369	0.0144
S.Em.±	0.06	0.03	0.77	0.9	1.17	0.02	0.02	0.2	0.18	0.06	0.19	0.12	0.0006	0.0009	0.0007
C.D.(P=0.05)	NS	0.28	2.42	2.79	3.57	0.01	0.16	0.66	0.61	0.14	0.74	0.36	NS	NS	NS

Effect of bio-fertilizers

Growth Characters

Bio-fertilizer inoculation significantly improved all growth parameters of fenugreek over control. Among treatments, NPK consortia recorded the highest plant height, dry matter accumulation and branching, closely followed by Rhizobium + PSB, while Rhizobium alone showed moderate improvement. The improvement in growth may be attributed to enhanced biological nitrogen fixation and phosphorus solubilization, leading to improved nutrient availability in the rhizosphere. Rhizobium enhances nitrogen supply, while PSB improves phosphorus availability, both of which are essential for root development and vegetative growth. Improved nodulation under bio-fertilizer treatments further enhanced nitrogen fixation, which increased chlorophyll content and photosynthetic activity. This resulted in higher biomass production and better crop growth rate. However, relative growth rate remained unaffected, indicating that treatments influenced total biomass rather than proportional growth efficiency. Better root–microbe interaction and improved soil biological activity under NPK consortia created a more favorable environment for plant growth, resulting in superior performance compared to other treatments. The results of present investigation indicating overall improvement in crop growth due to bio-fertilizers inoculation are in close accordance with the findings of Dutta *et al.* (2012), Raiyani *et al.* (2018), Bhutadiya *et al.* (2019) and Kumar *et al*. (2021),

Yield Attributes and Yield

Bio-fertilizer inoculation significantly improved all yield attributes including pods per plant, seeds per pod, pod length and test weight. The highest values were recorded under NPK consortia, followed closely by Rhizobium + PSB. The improvement in yield attributes is mainly due to enhanced nitrogen fixation and phosphorus solubilization, which improved energy transfer, flowering, pod formation and seed development. Better nutrient availability during reproductive stages ensured improved source–sink balance. Seed yield, haulm yield and biological yield were significantly higher under bio-fertilizer treatments, with NPK consortia showing the best performance. Rhizobium alone also improved yield over control, confirming the importance of biological nitrogen fixation in fenugreek productivity. However, harvest index was not significantly affected, indicating that increases in biomass were proportionally distributed between seed and straw yield. The superiority of NPK consortia can be attributed to synergistic interaction between nitrogen-fixing and phosphorus-solubilizing microorganisms, which improved nutrient availability, soil fertility and plant metabolic activity. The results of present investigation indicating overall improvement in crop growth due to bio-fertilizers inoculation are in close accordance with the findings of Ali *et al.* (2009), Metha and Patel (2011) Biswas *et al*. (2019) and Bhutadiya *et al.* (2019). The results of investigation corroborated findings of Nair *et al.* (2020), Shekhawat *et al.* (2018), Malav *et al.* (2018) and Teli *et al.* (2016).

Table 2 Effect of sulphur and bio-fertilizers on yield and harvest index of fenugreek

Treatments	Yield attributes				Yield			Harvest index (%)
	Pods plant^{-1}	Seed pod^{-1}	Pod length (cm)	Test weight (g)	Seed	Haulm	Biological	
Sulphur (kg ha-1)								
10	27.62	15.35	9.92	10.47	1444	3767	5211	27.71
20	28.33	15.96	10.48	10.87	1652	4185	5837	28.30
30	29.03	16.5	10.96	11.26	1780	4528	6308	28.22
40	29.75	17.13	11.41	11.69	1896	4860	6756	28.06
S.Em.±	0.17	0.09	-0.02	0.02	38	106	144	26.19
C.D.(P=0.05)	0.69	0.47	0.14	0.24	111	308	419	NS
Bio-fertilizers								
Control	26.93	15.22	10.15	10.28	1542	3842	5384	28.64
Rhizobium	28.09	15.98	10.47	10.97	1658	4196	5854	28.32
Rhizobium + PSB	29.72	16.76	11.03	11.48	1777	4637	6414	27.70
NPK consortia	29.99	16.98	11.12	11.55	1796	4663	6459	27.81
S.Em.±	0.17	0.09	-0.02	0.02	38	106	144	26.19
C.D.(P=0.05)	0.689	0.47	0.14	0.24	111	308	419	NS

Conclusion

Sulphur application up to 40 kg ha^{-1} and bio-fertilizer inoculation significantly improved growth, yield attributes and yield of fenugreek. NPK consortia performed best, followed by Rhizobium + PSB. Harvest index remained unaffected. Overall, integrated use of sulphur and bio-fertilizers is effective for enhancing fenugreek productivity

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Publication History

Received	17.06.2026
Revised	15.07.2026
Accepted	16.07.2026
Online	02.08.2026